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Interstellar Gamma Ray Lines from Low Energy Cosmic Ray Interactions

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Abstract. Evidence for the existence of low energy cosmic rays in the Galaxy comes from the COMPTEL observations of gamma ray line emission from Orion, and also from light element abundance data which seem to suggest a low energy rather than a relativistic Galactic cosmic ray origin for most of the light elements. The Orion and light isotope data are more consistent with a composition that is depleted in protons and α particles than with one which is similar to that of the Galactic cosmic rays. This low energy cosmic ray phenomenon appears to be highly localized in space and time in the Galaxy, and is probably associated with star formation regions similar to Orion.

Key words: Gamma Rays: theory – Galaxy: abundances – Nuclear reactions, nucleosynthesis, abundances

1. Introduction

The interactions of accelerated particles with ambient matter produce a variety of gamma ray lines following the deexcitation of excited nuclei in both the ambient matter and the accelerated particles. Apart from solar flares, nuclear deexcitation lines following accelerated particle interactions have so far only been observed from the Orion molecular cloud complex (Bloemen et al. 1994). The Orion observations, carried out with the COMPTEL instrument on the Compton Gamma Ray Observatory (CGRO) revealed emission features at 4.44 and 6.13 MeV, due to deexcitations in ^{12}C and ^{16}O. Since there are no significant long lived radioactive isotopes of nucleosynthetic origin that decay into the excited states of these nuclei, the observed lines must be produced contemporaneously by large fluxes of accelerated particles interacting in Orion. Gamma ray emission in the energy range from about 30 MeV to 10 GeV was also observed from Orion with the EGRET instrument on CGRO (Digel, Hunter, & Mukherjee 1995). However, the fact that these EGRET data do not require that the cosmic rays in Orion be enhanced relative to the relativistic Galactic cosmic rays observed near Earth, implies that the particles which produce the line emission in Orion are mostly low energy cosmic rays confined to energies below the effective pion production threshold.

The discovery of gamma ray line emission from Orion and the implied existence of large fluxes of low energy cosmic rays, not only in Orion but probably also elsewhere in the Galaxy, has led to renewed discussions on the origin of the light elements. It has been known for over two decades that cosmic ray spallation is important to the origin of ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B (Reeves, Fowler, & Hoyle 1970). It was shown that the relativistic Galactic cosmic rays (GCR) interacting with interstellar matter prior to the formation of the solar system may have produced the observed solar system abundances of ^{6}Li, ^{9}Be and ^{10}B (Meneguzzi, Audouze & Reeves 1971; Mitler 1972). These cosmic rays, however, cannot account for the abundances of ^{7}Li and ^{11}B. It is believed that about 10% of the ^{7}Li is produced in the big bang and that most of the remaining production is due to nucleosynthesis in stars (e.g. Reeves 1994). Recent measurements of the boron isotopic ratio, ^{11}B/^{10}B, in meteorites yielded values in the range 3.84 – 4.25 (Chaussidon & Robert 1995) which exceed the calculated GCR value by a factor of about 1.5. The implications of the Orion gamma ray observations on the origin of the light isotopes have been considered by Cassé, Lehoucq & Vangioni-Flam (1995) and Ramaty, Kozlovsky & Lingenfelter (1996). Unlike the GCR, low energy cosmic rays, similar to those which produce gamma ray line emission in Orion, could account for the meteoritic B isotopic ratio. It is in fact possible that the bulk of the light isotopes, except ^{7}Li, is produced by low energy cosmic rays in the Galaxy. Although ^{11}B could have been produced by neutrino spallation of ^{12}C in supernovae (Woosley et al. 1990), recent B and Be observations in stars of various metallicities (Duncan 1995) support a low energy cosmic ray origin for ^{11}B since neutrino spallation is not expected to produce much Be.

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The present paper is in large part a review based on a series of previous articles dealing with the gamma ray line emission from Orion and related subjects (Ramaty 1995; Ramaty, Kozlovsky, & Lingenfelter 1995a,b;1996). After a general discussion, we consider the implications of the gamma ray line observations on the composition, energy spectrum, energy deposition and energy density of the low energy cosmic rays in Orion. We also consider the ionization produced by these cosmic rays, and briefly review the possible origins of the accelerated particles. We then proceed to calculate the expected gamma ray line emission produced by low energy cosmic rays in the Galaxy. We base this calculation on the close relationship between the gamma ray line and light isotope production.

2. General Considerations

The gamma ray lines produced by accelerated particle interactions can be broad, narrow or very narrow (Ramaty, Kozlovsky, & Lingenfelter 1979). Broad lines are produced by accelerated C and heavier nuclei interacting with ambient H and He. The broadening of these lines (widths ranging from a few hundreds of keV to an MeV) is due to the motion of the accelerated heavy particles themselves. Narrow lines are produced by accelerated protons and α particles interacting with ambient He and heavier nuclei. The broadening in this case (widths ranging from a few tens of keV to around 100 keV) is due to the motion of the heavy targets which recoil with velocities much lower than those of the projectiles. Very narrow lines result from excited nuclei which have slowed down and stopped due to energy losses before emitting gamma rays. The broadening of these lines is due only to the bulk motion of the ambient medium (widths around a few keV or less for the interstellar medium).

There are two distinct processes which can lead to very narrow line emission: deexcitation of heavy nuclei embedded in dust grains and excited by protons or α particles (Lingenfelter and Ramaty 1976), and deexcitation of excited nuclei populated by long lived radionuclei. Line emission from dust is not discussed in the present article. Dust grains, however, may play an important role in the injection and acceleration of the low energy cosmic rays which produce the gamma ray lines (see below). Long lived radionuclei produced by accelerated particle bombardment can stop in ambient gas before they decay thereby producing excited nuclei essentially at rest. The most important such radionuclei are ^{55}Co($\tau_{1/2}$ = 17.5h), ^{52}Mn($\tau_{1/2}$ = 5.7d), ^{7}Be($\tau_{1/2}$ = 53.3d), ^{56}Co($\tau_{1/2}$ = 78.8d), ^{54}Mn($\tau_{1/2}$ = 312d), ^{22}Na($\tau_{1/2}$ = 2.6y), and ^{26}Al($\tau_{1/2}$ = 0.72my), all of which can be produced in accelerated particle interactions, for example ^{56}Fe(p,n)^{56}Co. Unlike the very narrow grain lines which are produced almost exclusively by accelerated protons and α particles, very narrow lines from long lived radioactivity can result from both these interactions and interactions due to accelerated heavy nuclei.

In the following discussion we shall need to make assumptions on the composition of both the ambient medium and the accelerated particles, on the energy spectrum of the accelerated particles, and on the interaction model. As these have been described in detail in Ramaty et al. (1996), we only give a brief summary here. For the ambient medium we assume a solar system composition (Anders & Grevesse 1989). For the accelerated particles we consider six different composition: solar system (SS), cosmic ray source (CRS), the ejecta of supernovae of 35M$_\odot$ and 60M$_\odot$ progenitors (SN35 and SN60), the winds of Wolf-Rayet stars of spectral type WC, and pick-up ions resulting from the breakup of interstellar grains (GR). The grain case is analogous to the anomalous component of the cosmic rays observed in interplanetary space (Fisk, Kozlovsky, & Ramaty 1974; Adams et al. 1991). Interstellar neutral atoms that penetrate into the solar cavity are picked up by the magnetized solar wind after being ionized by solar UV and charge exchange with solar wind protons. Because in the frame of the wind the ions acquire considerable energy during the pick up process ($m_i V^2/2$ where V is the speed of the wind), they form a seed population that is much more easily accelerated than the rest of the ambient plasma. For Orion it is conceivable that the equivalent incoming matter is essentially neutral dust that is broken up by evaporation, sputtering or other processes. The assumed GR abundances are SS abundances modified by depletion factors (Sofia, Cardelli & Savage 1994). The noble gas (He, Ne, Ar) abundances are set to zero and H/O = 2, assuming that the bulk of the H and O are in ice. The acceleration of pick up ions in Orion was also considered by Ip (1995).

The essential properties of these compositions are the following: SS, CRS and to some extent SN35 have large proton and α particle abundances relative to C and heavier nuclei. On the other hand, because of prior mass loss for SN60 and WC, and because H and He are essentially absent in dust, the SN60, WC and GR compositions are very poor in protons and α particles. There is no Ne in the GR composition. The WC composition is dominated by C and O and has some additional amount of ^{22}Ne.

All the calculations are carried out in a thick target model in which accelerated particles with given energy spectrum and composition are injected into an interaction region where they produce nuclear reactions as they slow down due to Coulomb interactions to energies below the thresholds of the various reactions. Energetically this is the most efficient way of producing the nuclear reactions; if the particles are allowed to escape at higher energies, then energy that would otherwise be available for producing nuclear reactions, is removed from the system rendering the process less efficient. Energetic efficiency is important for gamma ray line production in Orion because even under optimal conditions the deposited energy, and

the accompanying ionization if the medium is neutral, are very large. A model in which the particles escape from the interaction region with negligible energy loss is referred to as a thin target model. In a thick target the energy spectrum of the interacting particles is flatter (because of the energy losses) than their source spectrum; in a thin target the interacting particle spectrum is identical to the source spectrum. A 'thin target' situation can also arise without escape, namely when continuous particle acceleration compensates for the energy losses so that the spectrum of the interacting particles remains identical to their source spectrum.

Because the Coulomb energy losses depend on the charge of the particles, these losses reduce the importance for gamma ray production of heavy nuclei relative to lighter nuclei. Thus, for the compositions poor in protons and α particles (i.e. SN60, WC and GR), for which practically all the gamma ray production is due to C and heavier nuclei, the ratio of the line emission from Ne, Mg, Si and Fe to that from C and O is smaller in a thick target than in a thin target. This has an observable consequence: because C and O produce lines predominantly in the 4–7 MeV region while Ne–Fe produce lines at energies below 3 MeV, for identical source spectra and compositions, deexcitation line production below 3 MeV relative to that above this energy is smaller in a thick target than in a thin target. This is relevant for Orion, where, as we shall see, emission in the 1–3 MeV was strongly suppressed relative to the emission between 4–7 MeV.

The calculations that we present are carried out with two spectral forms for the accelerated particle source function,

$$\frac{dN_i}{dt}(E) = K_i\Big(\frac{E}{E_0}\Big)^{-1.5} e^{-E/E_0}, \tag{1}$$

and

$$\begin{aligned}\frac{dN_i}{dt}(E) &= K_i\Big(\frac{E}{E_c}\Big)^{-s} \quad \text{for} \;\; E > E_c \\ &= K_i \quad \text{for} \;\; E \le E_c,\end{aligned} \tag{2}$$

where the K_i's are proportional to the accelerated particle source abundances, E is energy per nucleon, and the parameters E_0 and E_c are allowed to vary over the broad range from 2 to 100 MeV/nucl. The nonrelativistic spectral index of 1.5 in Eq. (1) is the consequence (e.g. Ellison & Ramaty 1985) of shock acceleration with a compression ratio at its maximal value of 4; the exponential turnover characterizes the effects of a finite acceleration time or a finite shock size. There is little theoretical basis for the flat spectrum given by Eq. (2). It is a simple form that has been used in previous calculations of gamma ray line and light element production (e.g. Ramaty et al. 1995a; Cassé et al. 1995; Ramaty et al. 1996), and we use it here as well; as in the previous studies (Ramaty et al. 1995a; 1996) we take $s = 10$. We refer to the spectrum given by Eq. (1) as the strong shock spectrum and to that given by Eq. (2) as the flat spectrum.

Fig. 1. Gamma ray observations from Orion; below 30 MeV – COMPTEL data (Bloemen et al. 1994); above 30 MeV – EGRET data (Digel et al. 1995).

3. Gamma Ray Line Emission from Orion

Gamma ray line emission in the 3 to 7 MeV range was observed from the Orion complex with COMPTEL (Bloemen et al. 1994). We show the COMPTEL data in Fig. 1 together with the higher energy gamma ray emission observed from Orion with EGRET (Digel et al. 1995). The 3–7 MeV observations show emission peaks near 4.44 and 6.13 MeV, consistent with the deexcitations in ^{12}C and ^{16}O following accelerated particle interactions. This implies that the ambient matter in Orion is undergoing bombardment by an unexpectedly intense, locally accelerated, population of low energy cosmic rays. At other photon energies the COMPTEL observations reveal only upper limits. As we shall see, the 1–3 MeV upper limit places strong constraints on the composition of the low energy cosmic rays. Digel et al. (1995) have shown that the EGRET data can be understood in terms of a relativistic cosmic ray flux similar to that observed near Earth producing gamma rays in Orion via pion decay and bremsstrahlung. This implies that the low energy cosmic rays should be confined to energies below the effective pion production threshold (see also Cowsik & Friedlander 1995). In the following we shall be concerned with the properties and effects of these low energy cosmic rays.

3.1. Composition

In all the calculations of gamma ray production in Orion the ambient gas was assumed to have a solar system composition (Anders & Grevesse 1989). This should not suggest that there could be no departures from solar abundances in the ambient medium; such effects were simply

Fig. 2. Calculated gamma ray spectra for the cosmic ray source and the grain compositions, showing a mixed broad-narrow line spectrum (upper panel) and a broad line spectrum (lower panel); the very narrow lines in the lower panel are from long lived radionuclei. The predicted 0.847 MeV line flux in the upper panel is $5{\times}10^{-6}$ ph cm^{-2} s^{-1}.

not yet investigated. The results discussed here, therefore, pertain only to the accelerated particles.

Information on the proton and α particle abundances relative to those of C and heavier nuclei could be obtained from observations of the shapes of the gamma ray lines. In Fig. 2 we show theoretical gamma ray spectra for the CRS (cosmic ray source) and GR (grain) compositions calculated using Eq. 2 (flat spectrum) with E_c=20 MeV/nucl. (Spectra obtained with the strong shock spectrum, Eq. (1), are not very different.) The CRS spectrum (top panel) shows both broad and narrow lines, as well as very narrow lines from long lived radionuclei. The ^{12}C complex around 4.44 MeV clearly shows the narrow line superimposed on its broad counterpart. On the other hand, the narrow lines are absent in the GR spectrum (bottom panel) showing the effects of the absence of protons and α particles. However, there are still very narrow lines from the long lived radionuclei. To allow the shortest lived radionucleus ^{55}Co($\tau_{1/2} = 17.5$h) to stop before it decays, we assumed that the ambient density exceeds 2×10^6 cm^{-3}. By convolving spectra similar to those in Fig. 2 with Gaussians representing the COMPTEL energy resolution, Ramaty et al. (1995a) showed that the current data cannot yet rule out a mixed broad-narrow line spectrum (e.g. the CRS) even though the COMPTEL energy resolution at 4.44 MeV (FWHM$\simeq$300 keV, Schönfelder et al. 1993) would appear sufficient. A similar result was also obtained by Cowsik & Friedlander (1995).

Fig. 3. Deposited power that accompanies the production of the observed gamma ray line emission from Orion for the various compositions and energy spectra discussed in the text. The ambient medium is neutral and has solar system composition.

On the other hand, arguments of energetics tend to support an accelerated particle composition poor in protons and α particles. To demonstrate this, we calculate the deposited power that is associated with the production of the nuclear reactions in a thick target. It is given by

$$\frac{dW}{dt} = \sum_i A_i \int_0^\infty E \frac{dN_i}{dt}(E) dE \ , \qquad (3)$$

where the A_i is atomic number and $\frac{dN_i}{dt}$ is given by Eqs. 1 or 2. We emphasize that in a thick target, the ratio of the nuclear reaction rate to the deposited power is essentially independent of details of the interaction region, especially the density of the ambient gas. It depends mainly on the spectrum and composition of the accelerated particles. The composition of the ambient gas could play a major role but only if there were a substantial enhancement of the C and heavier element abundances relative

to H and He. Such an enhancement would reduce the deposited power. There is also a weak dependence on the state of ionization of the ambient gas, as the Coulomb energy losses are higher in a plasma (by about a factor of 2) than in a neutral gas. The results are shown in Fig. 3 for an ambient neutral medium. The top panel is for the strong shock spectrum (Eq. 1) and the bottom panel is for the flat spectrum (Eq. 2). The deposited power, normalized to the distance of Orion and the observed 3–7 MeV nuclear deexcitation flux (Bloemen et al. 1994), is shown as a function of E_0 or E_c for the various compositions. We see that the gamma ray line production is energetically most efficient for compositions that are poor in protons and α particles (i.e. the SN60, WC and GR compositions), favoring such compositions. However, as we shall see below, even in the most favorable cases, the rate of ionization of gas in Orion is extremely large.

We mention here that if the light isotopes are indeed produced mostly by low energy cosmic rays, then these cosmic rays must also be depleted in protons and α particles. The α particle depletion is necessary in order not to overproduce ^{6}Li; the proton depletion ensures a linear dependence of the Be and B abundances on the Fe abundance in stars of various ages (Duncan 1995). If the low energy cosmic rays are poor in protons and α particles they will produce Be and B from the breakup of accelerated C and O on ambient H and He; in this case both the target and projectile abundances could remain constant, leading to a linear growth of the Be and B abundances. On the other hand, the GCR would produce much of the isotopes from the breakup of C and O in the ambient medium whose abundances increase with time, leading to a quadratic growth.

Information on the composition of the heavy nuclei can be obtained from the observed gamma ray spectrum. In Fig. 4 we show calculations of the ratio R,

$$R = 2\frac{\int_{1\mathrm{MeV}}^{3\mathrm{MeV}} E_\gamma^2 Q(E_\gamma) dE_\gamma}{\int_{3\mathrm{MeV}}^{7\mathrm{MeV}} E_\gamma^2 Q(E_\gamma) dE_\gamma}, \tag{4}$$

for which Bloemen et al. (1994) set a 2σ upper limit of 0.13 (see also Fig. 1). We see that the CRS and SS predicted ratios are in disagreement with the observations by more than 3σ, and the SN35 and SN60 predictions are inconsistent at greater than 2σ. Modifications in the abundances, however, can invalidate these results. For example, for the SN60 case, by increasing the C abundance by a factor of 2, but leaving all the other abundances unchanged, we obtain $R \simeq 0.13$ for both E_0 or E_c equal 30 MeV/nucl. On the other hand, both the GR and WC compositions yield R's which are lower than the COMPTEL upper limit. However, while the WC composition predicts practically no emission in the 1–3 MeV region, the GR composition predicts significant broad line emission in this region, due to Mg, Si and Fe. The reduction in the overall 1–3 MeV emission for the GR case is caused by the absence of the 1.634 MeV line due to the lack of Ne in grains.

Fig. 4. Calculated values for the ratio R defined in Eq. (4) for various compositions. The upper limit established with COMPTEL is plotted at an approximate energy which satisfies the constraints imposed by energetics, line shapes and high energy gamma ray observations.

3.2. Energy Spectrum

We have already pointed out that the fact that the EGRET data do not require an enhancement over the locally observed GCR implies that the accelerated particles which produce the gamma ray line emission in Orion are confined to low energies, below the pion production threshold. On the other hand, the energetics discussed above require a hard spectrum. This can be seen from Fig. 3 which shows that for steep spectra (i.e. small E_0 or E_c) the deposited power becomes very large. Thus the combined COMPTEL–EGRET data imply that the low energy cosmic rays in Orion should typically have energies around a few tens of MeV/nucl.

The shapes of the observed gamma ray lines could place further constraints on the hardness of the accelerated particle spectra. For values of E_0 or E_c larger than

about 50 MeV/nucleon, for pure broad line spectra, the 4.44 and 6.13 MeV lines become very broad (see Ramaty et al. 1996 for details). Although the current COMPTEL data cannot yet rule out such spectra, future observations could employ line shapes to limit the hardness of the low energy cosmic rays.

Fig. 5. Energy density in low energy cosmic rays in Orion for various values of E_0 compared with the energy density in the local Galactic cosmic rays.

3.3. Low Energy Cosmic Ray Energy Density

Whereas the power deposited in Orion by the accelerated particles can be calculated independent of the total irradiated mass of ambient gas, the low energy cosmic ray energy density does depend on this total mass. We have calculated this energy density assuming a steady state in which the accelerated particles lose energy by Coulomb collisions in a neutral gas. As already mentioned, the energy loss rates in an ionized gas are higher by only a factor of 2.

The results are shown in Fig. 5, where $w(E)$ is the differential energy density measured in MeV cm^{-3} MeV^{-1}. The top (bottom) panel is for the CRS (WC) composition. Also shown is the energy density in the local Galactic cosmic rays (GCR) evaluated from direct cosmic ray observations and assuming a power law in momentum source spectrum (Skibo 1993). We see that for the CRS composition the low energy cosmic rays energy density exceeds the local GCR energy density by almost two orders of magnitude; for the WC composition the excess is only about a factor of 10.

3.4. Ionization of the Ambient Gas

For the SN60, WC and GR compositions and E_0 or E_c about 30 MeV/nucl, the deposited power is (2.5–5)x10^{38} erg s^{-1}. The total deposited energy depends on the duration of the irradiation. For example, if the irradiation lasts 10^5 years, the total energy requirement would be (0.8-1.6)x10^{51} ergs, equal to the total kinetic energy output of a supernova. Just such a supernova, occurring ~80,000 years ago in the OB association at $l = 208°$ and $b = -18°$, the same direction as the center of the gamma ray line source, was suggested by Burrows et al. (1993) from analyses of the X-ray emission from the Orion-Eridanus bubble (see also Ramaty, Kozlovsky & Lingenfelter 1996).

As it takes 36 eV of cosmic ray energy to produce an ion pair in neutral H, the above deposited power corresponds to an ionization rate of (4.3–8.7)$\times$10^{48} H atoms s^{-1} or (0.17–0.34) M$_\odot$ yr^{-1}. Even with no recombination, in 10^5 years the amount of H that would be ionized is only (1.7–3.4)$\times$10^4 M$_\odot$, which is significantly smaller than the current neutral H mass in Orion. Considering the current ionization rate per H atom, we obtain that ζ=(0.5–1.0)$\times$10^{-13}M$_5^{-1}$ s^{-1}, where M$_5^{-1}$ is the irradiated neutral H mass in units of 10^5 M$_\odot$. The effects of such a very large ionization rate have not yet been examined. It is nevertheless possible that a large fraction of the power that accompanies the gamma ray production is deposited in ionized gas.

3.5. Origin of the Low Energy Cosmic Rays in Orion

In considering the origin of the low energy cosmic rays in Orion, we distinguish the problem of the acceleration from that of the injection of the particles into the accelerator. The proposed acceleration mechanisms are shock acceleration, due to shocks associated with the winds of O and B stars (Nath & Biermann 1994) or shocks produced by colliding stellar winds and supernova explosions (Bykov and Bloemen 1994), and stochastic acceleration, due to gyroresonance with cascading Alfvén turbulence in the accretion disk of a black hole (Miller & Dermer 1995). The proposed injection sources are the winds of Wolf Rayet stars (the WC composition, Ramaty et al. 1995a), the ejecta of supernovae from massive star progenitors (c.f. the SN60 composition, Cassé et al. 1995; Ramaty et al. 1996), and the pick up ions resulting from the breakup of interstellar grains (c.f. the GR composition, Ramaty et al. 1995b;1996). The suppression of accelerated protons and

α particles relative to C and heavy nuclei (§3.1) finds an explanation in stochastic acceleration. This mechanism, however, does not predict the suppression of Ne and heavier nuclei relative to C and O (§3.1). The suppression of protons and α particles is relatively easily achieved by all the proposed injection processes. Concerning the heavier nuclei, Ne–Fe are strongly suppressed in WC, but less so in the SN60. The suppression of Ne in the GR composition is sufficient to account for the 1–3 MeV COMPTEL upper limit.

The comparison with solar flares is quite instructive (Ramaty et al. 1995;1996). The solar flare gamma ray spectra show much higher ratios of 1–3 MeV to 3–7 MeV fluxes than does Orion. It was shown (Murphy et al. 1991) that this enhanced emission below 3 MeV is, in part, due to the enrichment of the flare accelerated particle population in heavy nuclei. Such enrichments are routinely seen in direct observations of solar energetic particles from impulsive flares (e.g. Reames, Meyer & von Rosenvinge 1994). These impulsive flare events are also rich in relativistic electrons. On the other hand, in gradual events the composition is coronal and the electron-to-proton ratio is low. The acceleration in impulsive events is thought to be due to gyroresonant interactions with plasma turbulence while in gradual events it is the result of shock acceleration. The fact that the ratio of bremsstrahlung-to-nuclear line emission in Orion is very low lends support to the shock acceleration scenario.

4. Low Energy Cosmic Rays in the Galaxy

We now provide estimates of the Galactic gamma ray line emission expected from low energy cosmic ray interactions. We base these estimates on the close relationship between light isotope and nuclear deexcitation line production. In Fig. 6 we show the B to 3–7 MeV nuclear gamma ray production ratio, $Q(\mathrm{B})/Q(3-7)$, as a function of E_0 and E_c for the strong shock (Eq. 1) and flat (Eq. 2) accelerated particle spectra, and for the various compositions. We see that at the higher values of E_0 and E_c the ratio is not strongly dependent on composition. This is because both the B and the 3–7 MeV deexcitation photons are mostly produced from C and O. However, $Q(\mathrm{B})/Q(3-7)$ does depend quite strongly on the spectrum of the accelerated particles. For the subsequent estimate, we take $Q(\mathrm{B})/Q(3-7) \simeq 0.1$, which, for $E_0 = E_c = 20$ MeV/nucl, is a mean for the two assumed spectral forms.

To estimate the total B inventory in the Galaxy we first use the meteoritic B/H ratio given by Anders & Grevesse (1989) and a total Galactic mass of 5×10^{10} $\mathrm{M}_\odot$. This yields $N_\mathrm{B}\simeq3\times10^{58}$ atoms. However, as the meteoritic B/H is probably higher than the B/H measured in Pop I stars by a factor of 3 to 4 (Reeves 1994), we take the Galactic B inventory at the formation of the solar system to be approximately 10^{58} atoms, and assume that it was produced by low energy cosmic rays in about 5×10^9 years. This yields an average B production rate prior to the formation of the solar system of about 6×10^{40} atoms s^{-1}. We then further assume that current production rate is equal to this average and use $Q(\mathrm{B})/Q(3-7\mathrm{MeV}) \simeq 0.1$ to estimate a current Galactic 3–7 MeV photon production rate $Q_\mathrm{G}(3-7\mathrm{MeV}) \simeq 6\times10^{41}$ photons s^{-1}. In terms of this total Galactic production, the flux from the central Galactic radian is

$$\Phi_{3-7} \simeq \xi 10^{-46} Q_\mathrm{G}(3-7) \simeq 6\times10^{-5}\xi \text{ ph cm}^{-2}\text{ s}^{-1}, \quad (5)$$

where $0.5 \lesssim \xi \lesssim 2$ depending on the spatial distribution of the sources (Skibo 1993). Clearly this prediction is highly uncertain. The estimate of the current B production rate would be larger if there were significant destruction of B due to incorporation into stars; in this case we would predict a higher central radian flux. On the other hand, the current B production rate could be lower than the average rate prior to the formation of the solar system, in which case our prediction would also be lower. In addition, since the B to 3–7 MeV photon conversion depends on the spectrum of the accelerated particles, for values of E_0 or E_c larger than 20 MeV/nucl, the ratio would be smaller than

Fig. 6. Production ratios of B to 3–7 MeV nuclear deexcitation photons for various abundances and energy spectra.

the value we used, yielding a lower predicted central radian flux. Clearly much could be learned from an actual measurement of C and O deexcitation line emission from the direction of the Galactic center or elsewhere.

In Fig. 7 we compare our calculations with observations. None of these have revealed any line emission. The COMPTEL data (Strong et al. 1994) is continuum, most likely a combination of bremsstrahlung and inverse Compton radiation produced by relativistic electrons. The SMM upper limit refers specifically to line emission (Harris, Share, & Messina 1995). We obtained the calculated curves by normalizing the spectra shown in Fig. 1 to the 3–7 MeV flux of 6×10^{-5} ph cm^{-2} s^{-1} given above. While the calculations are not inconsistent with data, it is conceivable that with more sensitive instruments or with longer COMPTEL exposures, the predicted line emission could be observed.

Fig. 7. Predicted nuclear deexcitation line emission from the central radian of the Galaxy. The COMPTEL continuum observations (Strong et al. 1994) and the SMM upper limit on line emission (Harris et al. 1995) are also shown.

For the WC, SN60 and GR compositions and $E_0 = E_c = 30$ MeV/nucl the energy required to produce 1 B atom is about 1 erg (Ramaty et al. 1996). The current rate of B production of about 6×10^{40} atoms s^{-1} then implies a current total power deposition by low energy cosmic rays in the Galaxy of about 6×10^{40} erg s^{-1}. When compared with the energy deposition rate in Orion (§3.4), we find that about 200–400 Orion-like regions could be currently active in the Galaxy. This small number, and the fact that the irradiation time in Orion probably lasted for only 10^5 years, implies that the low energy Galactic cosmic ray phenomenon is highly localized in space and time, in contrast with the GCR whose spatial distribution is relatively uniform and their time dependence, as evidenced by meteoritic studies, is relatively constant in time.

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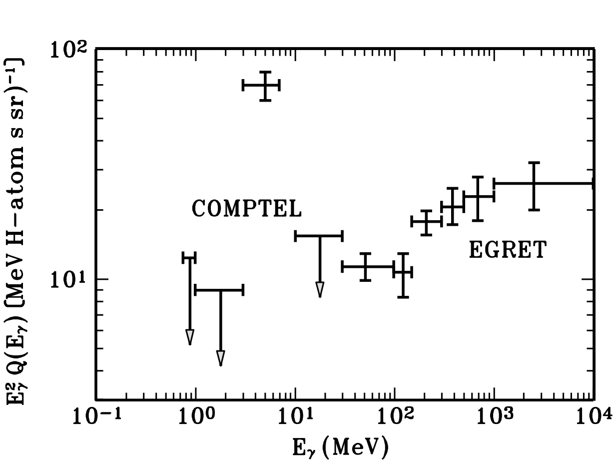
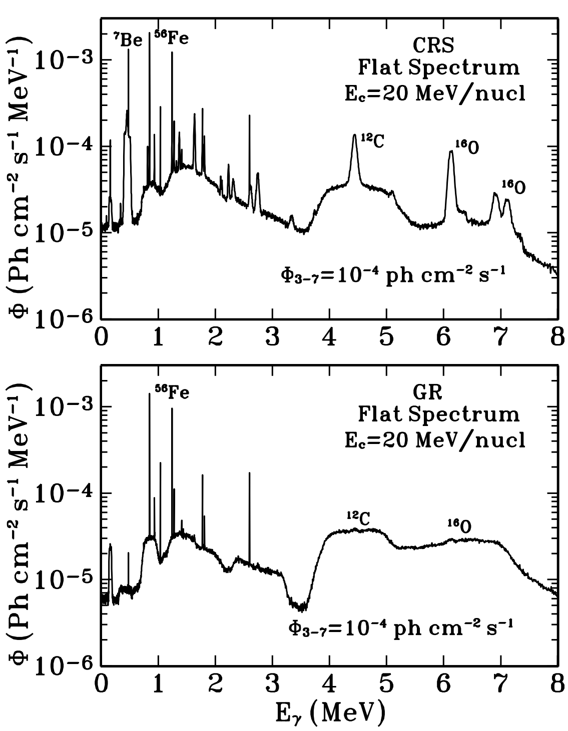
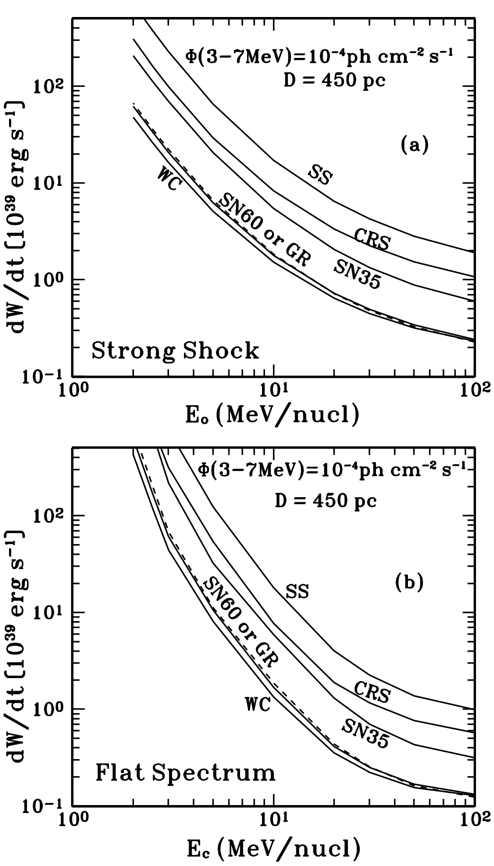


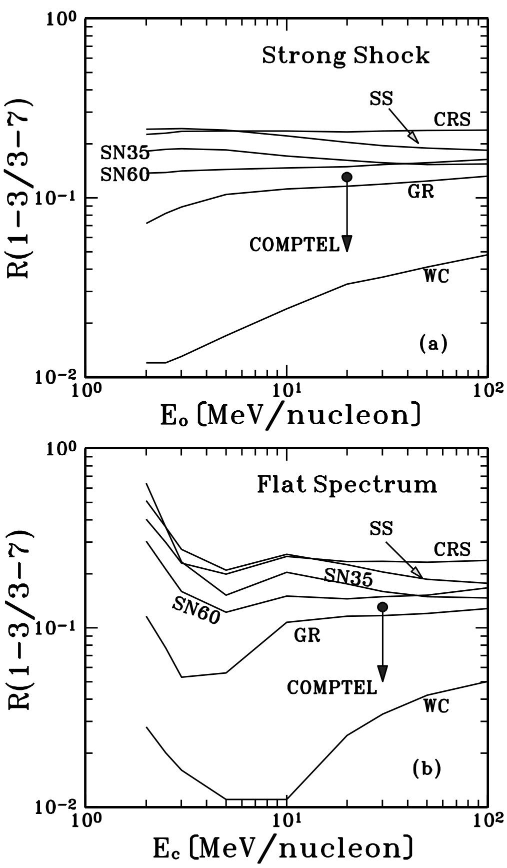
10^2
10^1
COMPTEL
EGRET
10^{-1}
10^0
10^1
10^2
10^3
10^4
E_γ (MeV)
$E_\gamma^2\, Q(E_\gamma)$ [MeV H−atom s sr)$^{-1}$]



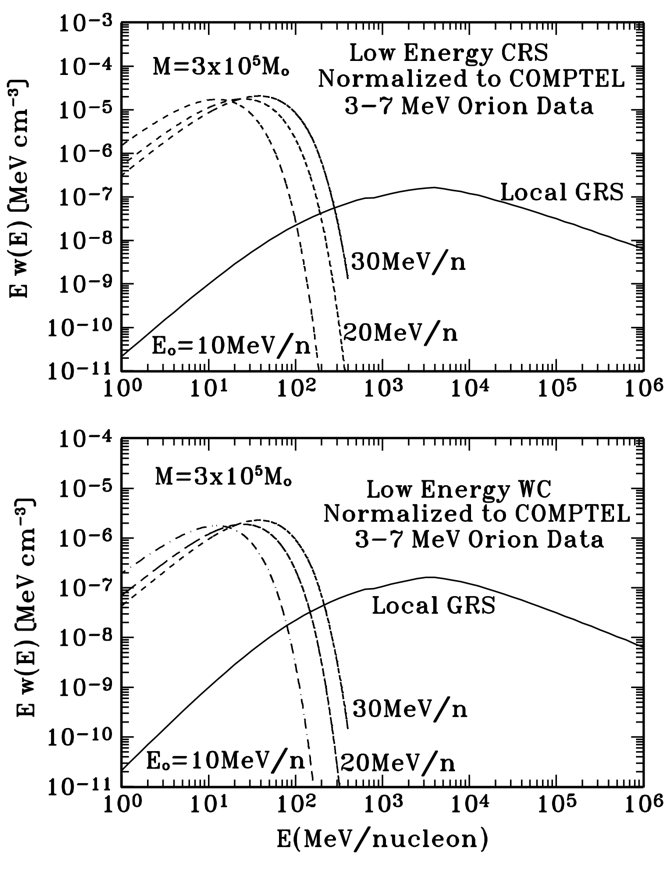
CRS
Flat Spectrum
E_c=20 MeV/nucl
^{7}Be
^{56}Fe
^{12}C
^{16}O
^{16}O
$\Phi_{3-7}=10^{-4}$ ph cm^{-2} s^{-1}
GR
Flat Spectrum
E_c=20 MeV/nucl
^{56}Fe
^{12}C
^{16}O
$\Phi_{3-7}=10^{-4}$ ph cm^{-2} s^{-1}
Φ (Ph cm^{-2} s^{-1} MeV^{-1})
E_γ (MeV)



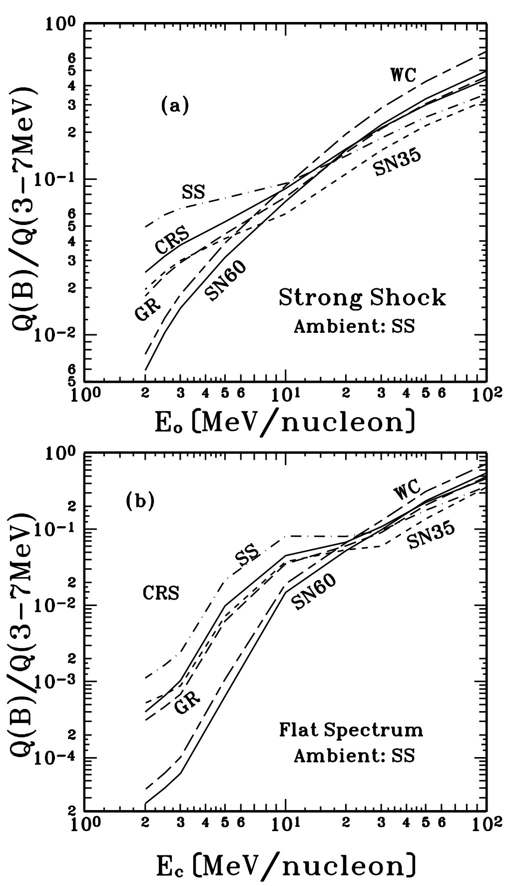
Φ(3−7MeV)=10⁻⁴ph cm⁻² s⁻¹
D = 450 pc
(a)
SS
CRS
SN35
SN60 or GR
WC
Strong Shock
dW/dt [10³⁹ erg s⁻¹]
Eₒ (MeV/nucl)
Φ(3−7MeV)=10⁻⁴ph cm⁻² s⁻¹
D = 450 pc
(b)
SS
CRS
SN35
SN60 or GR
WC
Flat Spectrum
dW/dt [10³⁹ erg s⁻¹]
E꜀ (MeV/nucl)



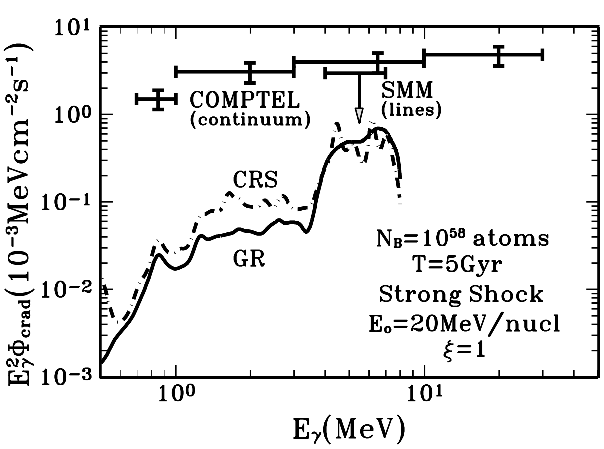
Strong Shock
SS
CRS
SN35
SN60
GR
COMPTEL
WC
(a)
R(1−3/3−7)
E₀ (MeV/nucleon)
Flat Spectrum
SS
CRS
SN35
SN60
GR
COMPTEL
WC
(b)
R(1−3/3−7)
E꜀ (MeV/nucleon)



M=3x10⁵M☉
Low Energy CRS
Normalized to COMPTEL
3-7 MeV Orion Data
Local GRS
30MeV/n
20MeV/n
E₀=10MeV/n
E w(E) [MeV cm⁻³]
Low Energy WC
E(MeV/nucleon)



(a)
WC
SS
CRS
GR
SN60
SN35
Strong Shock
Ambient: SS
Q(B)/Q(3−7MeV)
E₀ [MeV/nucleon]
(b)
WC
SS
CRS
GR
SN60
SN35
Flat Spectrum
Ambient: SS
Q(B)/Q(3−7MeV)
E_c [MeV/nucleon]



$E_\gamma^2\Phi_{crad}(10^{-3}\mathrm{MeVcm^{-2}s^{-1}})$
$E_\gamma(\mathrm{MeV})$
COMPTEL
(continuum)
SMM
(lines)
CRS
GR
$N_B=10^{58}$ atoms
T=5Gyr
Strong Shock
E_o=20MeV/nucl
$\xi=1$